REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
04-01-2008

2. REPORT TYPE
Final Report

3. DATES COVERED *(From – To)*
15 September 2006 - 15-Sep-07

4. TITLE AND SUBTITLE
Single-Photon detection using high frequency acoustic waves on GaAs/AlGaAs heterostructures

5a. CONTRACT NUMBER
FA8655-06-1-3051

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Professor Michael Pepper

5d. PROJECT NUMBER

5d. TASK NUMBER

5e. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Cambridge
Cavendish Laboratory
Madingley Road
Cambridge CB3 0HE
United Kingdom

8. PERFORMING ORGANIZATION REPORT NUMBER
N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
EOARD
Unit 4515 BOX 14
APO AE 09421

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
Grant 06-3051

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited. (approval given by local Public Affairs Office)

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The aim of the work within this grant has been to make a series of devices and perform a series of experiments that would demonstrate proof-of principle for the single-photon detector shown in Fig. 1. Much of this work is described in detail in the authors other publications [1-11]..

15. SUBJECT TERMS
Surface Acoustic Waves, Single Photon Detector, EOARD

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18, NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			BARRETT A. FLAKE
UNCLAS	UNCLAS	UNCLAS	UL	5	19b. TELEPHONE NUMBER *(Include area code)* +44 (0)1895 616144

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39-18

UNIVERSITY OF CAMBRIDGE

DEPARTMENT OF PHYSICS
CAVENDISH LABORATORY
J.J. THOMSON AVENUE
CAMBRIDGE CB3 0HE
UK

REPORT TO EOARD

Single-Photon detection using high frequency acoustic waves on GaAs/AlGaAs heterostructures

M. PEPPER-PRINCIPAL INVESTIGATOR

November, 2007

Introduction

The aim of our work within this grant has been to make a series of devices and perform a series of experiments that would demonstrate proof-of-principle for the single-photon detector shown in Fig. 1. Much of this work is described in detail in our publications [1-11].

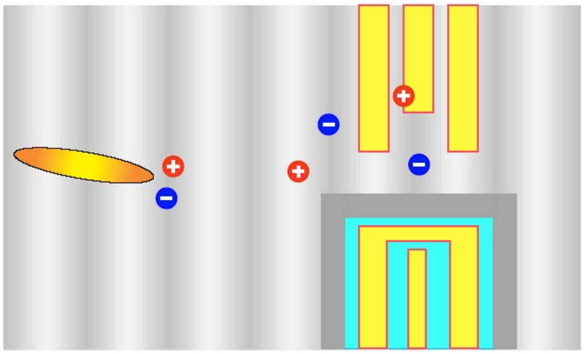

Fig 1.: SAW based single-photon detector. A single photon hits an undoped GaAs-AlGaAs heterostructure and creates an exciton (left). A SAW sweeps the electron from the exciton into a quantum dot where it is trapped (central upper). A point contact detector (central lower) then detects the presence of the electron.

As previously reported, in the first six months of this grant we studied single-electron detection and GHz light emission from SAW devices. During this final period of grant we have developed methods for creating SAW devices on undoped GaAs-AlGaAs heterostructures and we have made a detailed analysis of two aspects of the single-electron detection process.

1. Work on undoped Ga-AlGaAs heterostructures

The first part of our work here has centered on developing processes to make Ohmic contact to a SAW device patterned on an undoped GaAs-AlGaAs heterostructure. We have been successful in this. Fig. 2 shows our contact design, which involves four processing steps. In the first step, metallic gates are evaporated onto the surface and annealed (dark spotted regions in Fig. 2) so that they make electrical contact between the device surface and the interface region between the GaAs substrate and the AlGaAs barrier. In the second step, inducing gates are evaporated onto the device surface (darker yellow shapes in Fig. 2). When positive potentials are applied to these gates an electron gas is induced beneath them. At this stage, owing to alignment issues, there is no electrical contact between the annealed contacts and any electron gas the surface inducing gates can produce. This is achieved by putting down an insulating layer (red/green patch in Fig. 2) and then placing a set of large surface area gates (bright yellow tree shapes in Fig. 2) covering both the metallic contacts and the surface inducing gates.

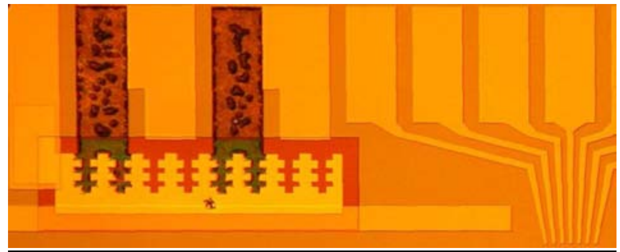

Fig 2: Image of Ohmic contacts showing the polyimide (red/green) insulating the top inducing gate (bright yellow) from the Ohmic contacts (dark spotted regions) and the surface inducing gate (light yellow).

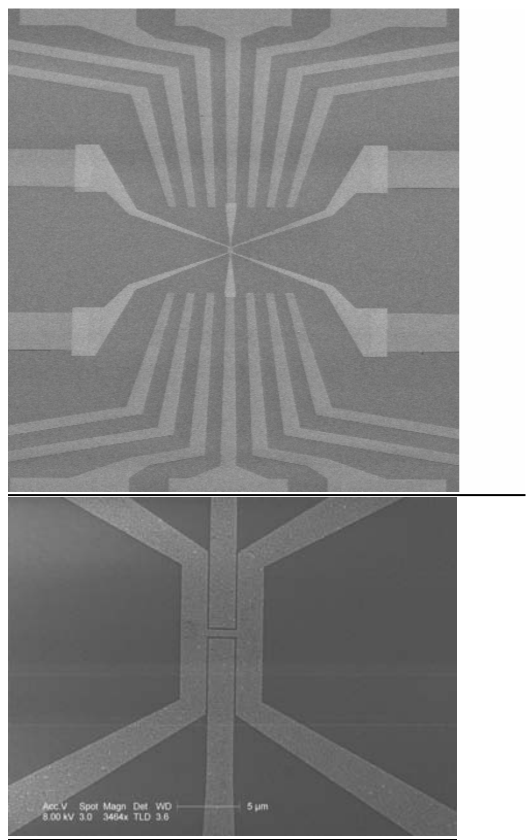

Fig 3: (Left) large scale image of e-beam patterned inducing gates. (Right) A detail showing the central split-gate structure.

The second part of our work in this section has been on creating induced SAW devices using e-beam lithography and measuring the SAW induced acousto-electric current through them at low temperature. Figure 3 shows a pattern for a single narrow split-gate channel. We are currently making electrical measurements of this device both with and without SAWs present. We have been able to demonstrate both SAW driven current and electrical control of this current.

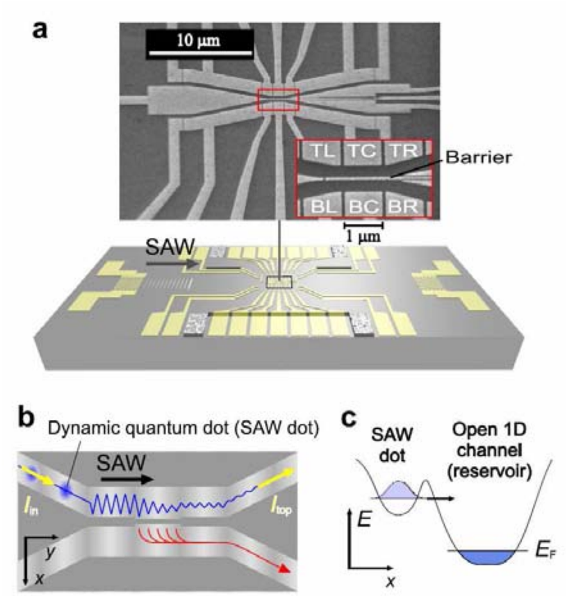

FIG. 4: (a), Illustration of the sample (bottom image) and SEM image showing the surface gates (top image). The inset shows the central 2.5 x 3.5 micon region of the device. (b) Simplified experimental circuit. SAWs carry a single electron in each potential minimum through the completely depleted top channel. At the weakest point of the tunnel barrier, electrons can tunnel into the open 1D channel

and escape into the bottom-right exit (red line). The injection current I_{In} and the output current I_{Top} are measured at the source (top left) and drain (top right) 2DEGs. The blue line in the top channel illustrates the oscillations of the wave function. (c) Channel potential across the tunnel barrier.

2. Single electron detection

We have continued our single-electron detection work in two ways: we have made the first observations of non-adiabatic single-electron motion [11] and we have made a detailed analysis of the few-electron capture and detection process.

The single-photon detector design shown in figure 1 would typically be less that a micron in length. The single-electron capture process would therefore take less than 300ps to occur. On this time scale electronic motion is highly coherent and any perturbation an electron encounters causes non-adiabatic unitary evolution of the single-electron wave function between its ground and excited states. This causes the electron charge distribution to oscillate on a few picosecond timescale and would thereby alter the detection process.

In order to gain a stronger understanding of these non-adiabatic processes and test this theory, we have performed a series of experiments where we force an electron from a narrow channel to a wide channel that has a tunnel barrier as one wall. Our experimental device is shown in figure 4 and evidence of an oscillating tunnel current is shown in figure 5. The oscillations that we see are very weak and can be modelled very accurately with exact solutions to the time-dependent Schrodinger equation for an approximate effective potential form. We therefore believe that whilst non-adiabatic motion is very interesting from a quantum information perspective (we have effectively observed the σz motion of a charge qubit in this experiment) it will not be a barrier to making an accurate single-photon detector. It is possible that such unitary motion could even be used as part of the design.

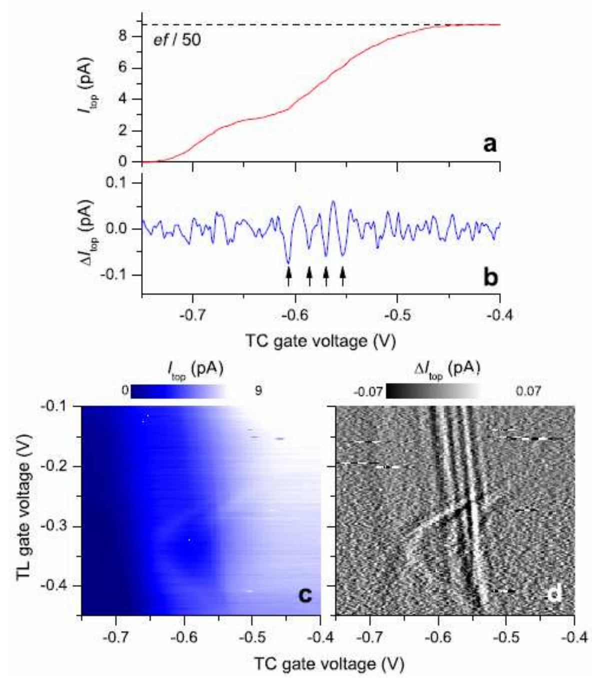

FIG. 5: The behaviour of the output current I_{top} from the top channel as top centre (TC) gate voltage is swept. (a) A line plot of I_{top}. As TC gate voltage is swept negatively, electrons are squeezed out of the top channel, and hence I_{top} decreases from the quantised current ef=50. (b) The value ΔI_{top} where a smoothed background has been subtracted reveals a set of weak but clear oscillations (four dips are indicated by arrows). (c) A colour plot of I_{top} as a function of TC and top left (TL) gate voltages. (d) ΔI_{top} plot shows reproducibility of the oscillations up to four (or maybe five) periods. We believe these oscillations are the result of coherent time evolution of the single-electron wave function within the dot. The visibility of the oscillations is ~1%.

Our work on few-electron capture [10] was also performed with the device shown in figure 4. It has enabled us to make estimates for the electron addition-energies of a SAW induced quantum dot. This was done by measuring the average tunnel current out of a series of SAW induced quantum dots and using a simple stochastic tunnelling model to extract the energies. We found that in going from considering single electron dots to two electron dots, the tunnelling rate increased dramatically. This implies that the Coulomb interaction is only weakly screened in these dots. These results suggest that if the detector design in figure 1 were altered to have a series of different quantum dots and detectors with different tunnel barrier heights we could detect multiple photon bursts on a much shorter time scale than would be possible with a single dot and detector.

3. Future Work

We could create a variety of dot and detector devices on undoped heterostructures and go through a small number of cycles to optimise their electrical operation with SAWs. These devices could then be tested in an optical cryostat to determine their success at single-photon detection.

References

[1] *Experimental investigation of the surface acoustic wave electron capture mechanism.* M. Kataoka, C. H. W. Barnes, H. E. Beere, D. A. Ritchie, M. Pepper. Phys. Rev. B 74 (8): Art. No. 085302, pages 4 AUG 2006 Cited: 1

[2] *Quantum-dot thermometry of electron heating by surface acoustic waves*. R. J. Schneble, M. Kataoka, C. J. B. Ford, C. H. W. Barnes, D. Anderson, G. A. C. Jones, I. Farrer, D. A. Ritchie,M. Pepper. Appl. Phys. Lett. 89 (12): Art. No. 122104, pages 3 SEP 18 2006 Cited: 3

[3] *Examination of surface acoustic wave reflections by observing acoustoelectric current generation under pulse modulation.* M. R. Astley, M. Kataoka, R. J. Schneble, C. J. B. Ford, C. H. W. Barnes, D. Anderson, G. A. C. Jones, H. E. Beere, D. A. Ritchie, M. Pepper. Appl. Phys. Lett. 89 (13): Art. No. 132102, pages 3 SEP 25 2006 Cited: 2

[4] *The effect of pulse-modulated surface acoustic waves on acoustoelectric current quantization.* M. Kataoka, C. J. B. Ford, C. H. W. Barnes, D. Anderson, G. A. C. Jones, H. E. Beere, D. A. Ritchie, M. Pepper. J. Appl. Phys. 100 (6): Art. No. 063710, pages 4 SEP 15 2006 Cited: 4

[5] *Examination of multiply reflected surface acoustic waves by observing acoustoelectric current generation under pulse modulation.* M. R. Astley, M. Kataoka, C. J. B. Ford, C. H. W. Barnes, D. Anderson, G. A. C. Jones, I. Farrer, H. E. Beere, D. A. Ritchie, M. Pepper. Phys. Rev. B 74 (19): Art. No. 193302, pages 4 NOV 2006 Cited: 0

[6] *Surface-acoustic-wave-driven luminescence from a lateral p-n junction.* J. R. Gell, P. Atkinson, S. P. Bremner, F. Sfigakis, M. Kataoka, D. Anderson, G. A. C. Jones, C. H. W. Barnes, D. A. Ritchie, M. B. Ward, C. E. Norman, A. J. Shields. Appl. Phys. Lett. 89 (24): Art. No. 243505, pages 3 DEC 11 2006 Cited: 3

[7] *Single-electron population and depopulation of an isolated quantum dot using a surface-acoustic-wave pulse.* M. Kataoka, R. J. Schneble, A. L. Thorn, C. H. W. Barnes, C. J. B. Ford, D. Anderson,G. A. C. Jones, I. Farrer, D. A. Ritchie and M. Pepper. Phys. Rev. Lett. 98 (4): Art. No. 046801, pages 4 JAN 26 2007 Cited: 1

[8] *Collapse of nonequilibrium charge states in an isolated quantum dot using surface acoustic waves.* R. J. Schneble, M. Kataoka, C. J. B. Ford, C. H. W. Barnes, D. Anderson, G. A. C. Jones, I. Farrer, D. A. Ritchie and M. Pepper, Phys. Rev. B 75 (11): Art. No. 115310, pages 5 MAR 2007 Cited: 0

[9] *Temporal characteristics of surface-acoustic-wave-driven luminescence from a lateral p-n junction.* J. R. Gell, M. B. Ward, A. J. Shields, P. Atkinson, S. P. Bremner, D. Anderson, M. Kataoka, C. H. W. Barnes, G. A. C. Jones and D. A. Ritchie, 2007, Appl. Phys. Lett., 91, 013506, pages 3 Cited 0.

[10] *Energy-dependent tunnelling from few-electron dynamic quantum dots* M. R. Astley, M. Kataoka, C. J. B. Ford, C. H. W. Barnes, D. Anderson, G. A. C. Jones, I. Farrer, D. A. Ritchie, and M. Pepper, Phys. Rev. Lett. 99, 156802 (2007).

[11] *Coherent time evolution of a single-electron wave function*, M. Kataoka, M. R. Astley, A. L. Thorn, D. K. L. Oi, C. H. W. Barnes, C. J. B. Ford, D. Anderson, G. A. C. Jones, I. Farrer, D. A. Ritchie, and M. Pepper, to be published.